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1.0 SUMMARY

During this report period the work of Reports RR-19 and RR-20 have been corelated and analyzed together with new material, which summarizes one phase of the program using the Pulse-Jet Analog.

Report RR-19 studied the effect of Valve Forward Resistance on performance at one frequency.

Report RR-20 extended the study, including excitation frequency as a variable parameter.

The present report which studies the basic reasons for the behavior which was discovered in the earlier work, shows the reasons for the improved performance which has been predicted.

2.0 INTRODUCTION

This report describes work accomplished on item 1.7 of Exhibit A, Supplementary Agreement No. 5 of Contract AF33 (600)-5860 during the month of December, 1953.

This is the third report to be submitted describing the use of the Pulse-Jet Analog as a design tool for development purposes. The report is submitted by the American Helicopter Co., Inc., describing the study program being conducted by Paul S. Veneklasen, Consultant in Acoustics.

The work was carried out and is reported by Paul S. Veneklasen, and staff members W. B. Snow, G. F. Brockett, and M. O. Herwick.

3.0 D I S C U S S I O N: INTERPRETATION OF DATA FROM SEPTEMBER, OCTOBER AND NOVEMBER REPORTS:

The tests which have been conducted thus far in our work with the Pulse-Jet Analog, together with the data here presented, complete a phase of a program which offers certain useful conclusions. This work has been done using a simple form of the Analog as shown in Figure 3.2-1, page 36 of RR-19.

The use of this simple form of the Analog implies that many complicating factors have been temporarily eliminated; we trust not ignored. This implies that the results obtained thus far express idealized conditions. We may rather say that they predict the potential improvement which may be expected from certain modifications in Pulse-Jet engines. This is to admit that, when and if such changes are reduced to practical form, more or less compromise of the potential improvement may be expected. Nevertheless, it is important at this point to express clearly the meaning and form of the great potential improvement in Pulse-Jet design which has been disclosed by the work with the Pulse-Jet Analog.

3.1 S Y M B O L S:

At this point in the program it becomes advantageous to establish a list of symbols to facilitate discussion and labeling of data and graphs.

ANALOGOUS TERMS

ELECTRICAL ANALOG Symbol	ELECTRICAL ANALOG Meaning	ENGINE Symbol	ENGINE Meaning
I_{S-tot}	= Average current flow into Line when current is adjusted for zero flow during quiescent period (Milli-amperes)	U_{tot}	= Total energy expended per second by combustion of fuel
I_{S-av}	= Average source current delivered to Line by the Source (Energy Addition Analog). May be adjusted to any value from zero to I_{S-tot} (Milli-amperes)	U_{av}	= Total increase in mass flow due to fuel alone
E_{L-in}	= Voltage measured at input of Line (Volts)	P_{in}	= Chamber pressure near valves
I_o	= Line Output Current. Sub-av indicates average value as read on a meter (Milli-amperes)	U_o	= Volume velocity of gas flow at exhaust of engine tube = $v_o A_o$ = exhaust velocity x area of exhaust tube
I_v	= Valve Input Current (Milli-amperes)	U_v	= Volume Velocity of air flow through valves
R_{v-in}	= Valve Forward Resistance, i.e., resistance to I_v for direction of flow into the Line. This may be a constant or variable value during the open period (ohms)		Same symbol for acoustic resistance of valves, which is ratio of P_{in}/U_v
t	= Input Pulse Length (Seconds)		Same
T	= Cycle period = 1/f, f = operating frequency		Same
F_{spec}	= Specific Thrust $= \dfrac{E_{L-in}}{I_{S-tot}}$ (Ohms)		Same $= \dfrac{\text{Thrust}}{\text{Rate of fuel flow}}$

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3.2 WAVE MOTION VS. VALVE TERMINATION:

The principal factor which permits potential improvement in Pulse-Jet performance requires a thorough understanding of the dependence of wave motion in the Pulse-Jet tube upon the air flow conditions at the ends of the tube. At the exhaust end we clearly have an open tube, one which permits the free flow of gases. (For the present we ignore the complications due to acoustical radiation, turbulence, vortex formation, etc.). At the valve end we have a complex condition which depends upon many factors, principally the nature and constants of the valves. For the present purpose we assume that the valves open and close instantly as pressure crosses atmospheric value, that the valves pass negligible current with positive chamber pressure and that, when the valves are open, the air flow is proportional to the negative pressure, i.e., the flow is controlled by a pure resistance. This flow resistance is a variable parameter in the system which can be adjusted at will in the Analog.

3.2.1 Valve Termination:

An electrical line or an acoustic tube can be terminated, i.e., given an end condition, such that all energy which travels along the line is completely absorbed when it reaches the end. This value of termination for a simple line or tube is called the Characteristic Resistance. When so terminated, it is clear that a resonant condition cannot exist, because resonance implies successive reflections of energy.

We are here concerned with the value of resistance (to air flow in the case of the acoustic tube, or to current flow in the case of the electrical line or tube analog) which the valves present when open.

We assume that the valves open instantly when negative pressure arrives. The continuing wave motion in the tube is profoundly determined by this value of resistance, whether it is equal to Characteristic Resistance, or whether it is greater or less than characteristic value.

Fig. 3.1 illustrates these effects in the electrical line, and we here discuss also the analogous case in the acoustic tube. The curves show the wave behavior in the line following a single pulse of excitation.

The central column of curves shows the behavior of the system when the open valves present Characteristic Resistance.

The left group is for a high value of R_{V-in}, and the right group is for a low value of R_{V-in}. The text with each column of curves describes the pulse behavior successively in terms of the Source Current I_S, the Line Input Voltage E_{L-in}, the voltage at a mid-point on the line E_{L-mid}, the Valve Input Current I_v, and the Line Output Current I_o.

The differences in behavior are stressed in the text of Fig. 3.1. The most important feature is this: There is one value of terminating resistance for which there can be no wave motion after the first reflection at the open end of the tube, because the energy is all dissipated in the valve resistance, whereupon reflection ceases. If the value of valve resistance is either greater or less than this characteristic value reflection of energy at the valves will occur, the nature of the reflection being very different in these two cases. The reflection will be stronger and therefore resonance will be stronger the greater the valve resistance differs from characteristic value, i.e., either zero or infinite. Infinite or any high value is hardly useful since valve current is restricted. It is clear that an extremely low value of resistance is to be desired.

These charts give a quantitative picture of wave performance within a tube. For example, the following correlations are of interest:

1. At the time of the initial pulse, the Line is quiescent and its input terminals should present characteristic resistance. The input pulse has a peak current of 6.7 ma. and develops a peak voltage of 27 volts, whereupon the resistance is $27/6.7 \times 10^{-3} = 4000$ ohms. (Incidentally, our Line is not strictly a classical line in that the input capacity was

increased and shunt damping resistors were added on an empirical basis to improve pulse transmission. Hence its characteristic resistance is not strictly calculable).

2. Note that the first pulse of output current is the same in all three cases. This should be independent of the valve forward resistance altogether, because the wave has not yet returned to be influenced by the valves. In fact, it can be shown that, if the source current were adjusted to a zero quiescent value (rather than an average of zero) and if there were no losses in the line, then the total flow of charge (charge = Integral of current with respect to time) from the output should be twice the current delivered by the source. (In our case this does not show, at least by a double-peak current, because, due to imperfection of the line, the output pulse is somewhat wider than the input pulse). Reasoning is as follows:
Suppose the input charge causes a positive voltage. If only unit charge flowed out the tailpipe, the line would be in an equilibrium state. But an excess unit charge flows outward to create the deficiency which produces the next negative voltage pulse. Incidentally, this negative pulse of voltage at the input end of the line will be double the original voltage pulse because all the charge is present in the tube during this pulse, whereas for the original pulse the charge was being inserted during the pulse. Hence for a line having an open circuit end and a short circuit end (i.e., a tube with one closed end and one open end) in free resonance, the charge which flows during each pulse from the open end will be double the excess charge which appears at the closed end.

3. The interchange of energy is interesting to consider. When the pulse is at the closed end of the tube, the energy associated with the pulse is pressure energy, i.e., potential energy. When the pulse arrives at the open end, the energy is in kinetic form, i.e., energy associated with the gas motion. Thus the wave motion in a tube may be viewed as a continual interchange between potential and kinetic energy. This concept, in the case of an electrical line, presents a considerable

strain on analogy. The potential energy is duly represented as potential energy associated with the excess charge on the capacitors. However, inasmuch as no significant mass is associated with current flow, it is difficult offhand to find an analogy for the kinetic energy. The answer is that the energy is stored in the magnetic field of the inductances of the Line. However, it is much simpler and apparently quite rigorous to associate a fictitious mass density with the electrical current, whereupon the analogy becomes quite straightforward.

3.2.2 Strength of Resonance:

Since the operation of the Pulse-Jet engine is recognized to be fundamentally dependent upon the resonance of a gas column in a tube, it is natural to inquire what factors influence the strength of resonance and how the parameters of the system may be adjusted to achieve the maximum benefit from resonance.

The curves of Figs. 3.4, 3.5 and 3.6 of RR-20 clearly indicate two controlling factors, which agree with the story of Fig. 3.1 of the present report. The strength of resonance is indicated by the variation in response between peaks and dips of the thrust curves. It is clear that the resonant peaks are most accentuated by using the lowest possible value of Valve Forward Resistance. It has been pointed out that the resonant peaks are also strong if the valve end is firmly closed, and indeed this fact was used in the tests which lead to the development of the artificial line, but this condition is hardly useful for an engine. It is also clear that there are many possible resonant modes in which an engine with low valve resistance may operate. The condition which favors strong resonance also favors high specific thrust.

The second factor which favors strong resonance is short combustion time, which again favors high specific thrust. (See Sec. 3.3-1)

It is of interest to note that the frequency of maximum resonance for high valve resistance is a frequency of nearly minimum resonance with low resistance valves. There is also

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reason to believe that there may be more than one resonant mode possible with high resistance valves, but only one appears with the values used in these tests.

3.3 FREQUENCY OF MAXIMUM THRUST:

Once it has been discovered that there are many possible operating modes, it is of interest to determine what distinguishes a given frequency of peak thrust. Accordingly, a particular mode, the 600 cps mode with 650 ohm valve resistance and a pulse length of .17 milli-seconds was chosen, and a series of oscilloscope traces arranged at peak performance and at neighboring frequencies to discover the determinants of optimum operation. This series is shown in Fig. 3.2. Controlling factors are not exactly obvious. Note first the horizontal series for valve input current, with attention to the state when the next pulse of input current is inserted. Note that the performance peak corresponds to the condition that the input pulse is injected just as a pulse of valve input current is finishing. In neighboring curves it is clear that the input pulse comes either too late or too early. The same trend is evident by examining the traces of line input voltage. Note that in the 600 cps case the input pulse causes the input voltage to rise just after the negative induction voltage has returned to zero.

It is clear from Fig. 3.1-C that there are many such possible moments for reinforcement in a resonant line. These are related to operating frequency in the following manner:
Two points of view may be adopted to explain the resonant frequencies;

1. Assume that the primary resonant mode of the tube with low valve resistance is the half wave mode with frequency = f_1. (f_1=(approx.)2000 cps in the case of our electrical line). Then any signal which has a harmonic at f_1 cps will excite the tube. Our input pulse is a signal having many harmonics. Hence when the pulse frequency f_n is such that $nf_n = f_1$, the system will resonate, so that $f_n = f_1/n$.

This formula gives only poor approximation to fact. Note, however, that the stronger a given harmonic of the input pulse nf_n, the more strongly the system should resonate. This explains the efficacy of short combustion time in encouraging resonance, because the shorter the pulse, the more prominent are the harmonics in the excitation.

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2. Note in Fig. 3.1 that there are many points in the decaying wave at which new energy can be injected just after a negative pulse of line input voltage. If these voltage pulses were infinitely short, these points would come at 0.5 milli-second intervals after the first input pulse. Hence the period could be any values

$$T_n = n \times .5 \times 10^{-3} \text{ sec.}$$

or any frequency

$$f_n = 1/T_n = 2000/n \text{ cps,}$$

which gives the same conclusion as before. Incidentally, the short pulse condition is well illustrated in Fig. 3.3 of RR-20. With longer input pulses the first interval is lengthened. The elapsed time must be at least .5 milli-seconds plus the pulse time t. Thereafter the next times come at intervals of .5 milli-seconds. Hence,

$$T_n = t + n \times .5 \times 10^{-3} \text{ sec.}$$

and the distorted "sub-harmonic" series results,

$$f_n = \frac{1}{t + n \times .5 \times 10^{-3}}$$

If one attempts to fit the resonant frequencies represented by the series from Fig. 3.4 of RR-20, using a pulse time $t = .54 \times 10^{-3}$ sec., one is disappointed. The experimental series of frequencies is 1220, 880, 590, 460, 380, 315. It is more enlightening to calculate values of t for each of these frequencies. The following series results:

f_n	T_n	t	f_n (t approaching 0)
1220	$.82 \times 10^{-3}$	.32	2000
880	1.14	.14	1000
590	1.69	.19	667
460	2.17	.17	500
380	2.64	.14	400
315	3.18	.18	333

Hence a fairly constant value fits, except for the highest frequency. On examining the data more closely one finds that the pulse of input voltage is shorter than the input current pulse. Thus at the present stage it appears that the operating frequencies will be given by a series of "sub-harmonics" of the half-wave resonant frequency with a considerable deviation which is determined by the combustion time. This concept can be checked with more extensive, rather simple tests.

The suggestion given in RR-20 is to be stressed, namely: it appears that in addition to the usual control of thrust by means of fuel flow, another method appears to be possible; by choosing the mode of operation, using a high frequency mode for maximum thrust and a lower frequency mode for lower thrust, but much greater specific thrust.

3.4 INFLUENCE OF VALVE FORWARD RESISTANCE ON AIR INDUCTION:

In explaining the great increases in thrust and specific thrust which are predicted by the Pulse-Jet Analog, two points of view may be taken, both of which are admirably indicated in the data.

1. Thrust is the integrated average pressure difference over the shell of the engine. The thrust figures which are given by the present form of the Analog are read from a voltmeter, which measures the average net positive voltage at the input of the line, corresponding to the average positive pressure across the valves. The oscillograph traces show admirably how an increase results from low valve resistance because the negative portions of input voltage are largely eliminated.

2. Thrust is the average rate of change of momentum produced in the gases handled by the engine. The oscillograph traces of Line Output Current and Valve Input Current also clearly substantiate the second point of view by indicating that a much larger amount of current flows when the valve resistance is low, and the periods of reverse current flow are eliminated. This relation is shown quantitatively in Fig. 3.3, which shows how the valve input current and line output current are controlled by R_{V-in} and t. Theory indicates that thrust is proportional to the average of the square of the output current.

Incidentally, it should be stressed that the Analog is so set up that inherently the average output current must equal the average valve input current, just as in the actual engine the total mass flow out the tailpipe must equal the total air inflow at the valves, except for the small proportion of fuel.

The conclusion from Fig. 3.3 is that, for a given input pulse a much larger amount of total flow results if the valve resistance is low and if the pulse length is short.

3.5 INFLUENCE OF COMBUSTION TIME ON PEAK PRESSURE:

All theoretical treatments of Pulse-Jet performance have indicated that higher peak pressures will be produced by shorter combustion time. The data produced thus far by the Analog has clearly demonstrated this fact. In fact, for isolated pulses the corelation is inherent in the system: For isolated pulses the instantaneous values during the input pulse, are such that

$$\frac{E_{L-in}}{I_S} = \text{Characteristic Resistance} = \text{Constant}$$

If the current pulse length, t, linearly decreases, maintaining the same value of total charge flowing during the pulse, the peak current must increase linearly. Therefore, E_{L-in} must also increase linearly with decreasing t. For isolated pulses this property is independent of valve resistance, but for repetitive operation the situation is not so simple.

3.6 VALVE CONDITION IN PRESENT ENGINES:

It is important in assessing the potentiality of the Pulse-Jet engine to know what is the Valve Forward Resistance at present. We would like to have a direct measurement of this factor whose importance has been shown by the Analog. In the absence of direct measurement we call attention to the following:

1. The literature is full of experimental evidence that backflow into the tailpipe occurs during part of the cycle. This has been shown directly by deposit of trace powders. It has been shown in numerous studies using Schlieren photography.
2. Theoretical works on the Pulse-Jet cycle have stressed the importance of re-entrant flow in the tailpipe and its function of increasing the mass of the charge ejected with each cycle.
3. The importance of the flare on the end of the tailpipe is proved experimentally. Its function is not so clearly demonstrated but it is thought to assist the backflow of air into the tailpipe.
4. In our own recording of the pressure trace just inside the valves, we interpret the trace to show a return positive wave before re-ignition. However, the corelation of pressure trace with flame intensity has not yet been accomplished to prove this point.

The Analog indicates that all these factors are consistent only with the existence of forward tube termination which is larger than characteristic impedance.

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3.7 SUMMARY OF CONDITIONS FOR IMPROVED PERFORMANCE:

Thus far in the work with the Electrical Analog of the Pulse-Jet engine there has been definite indication of vastly greater potential performance possibility, both as regards the amount of thrust which could be achieved with a given size of package, and the specific thrust. We summarize here the conditions which should be provided for improved performance:

1. The valve system should be so altered as to provide a minimum possible resistance to the inflow of air during the induction part of the cycle. The tube should be wide open during this time. The seal of the valve against reverse flow of gas should be maximum.
2. All pertinent factors should be adjusted to assure that combustion is completed in the shortest percentage of the operating cycle period.

3. The valve action should be as instantaneous as possible, i.e., the process of opening and closing should occur as rapidly as possible.

3.8 DESIGN OF AN EXPERIMENTAL ENGINE:

The achievement of the above factors for improved performance in a practical engine may be quite difficult, inasmuch as there are inherent contradictions. However, for the immediate purpose it is sufficient to provide a working arrangement, however impractical-appearing, for the specific purpose of testing the principles which have been discovered. The following are suggestions for this end:

1. Valving might be accomplished with a rotating shutter, having a projecting segment which covers one end of the Pulse-Jet tube for the desired period which is, at most, the 1/2-wave resonant period of the tube. For example, in a 6.75" engine which presently operates at about 150 cps, the 1/2-wave period is 1/300 sec., so that the shutter should be closed no more than about 3.3 milli-seconds. With this scheme the tube can be completely open the remainder of the cycle.

   The speed of rotation should be adjustable to test the various modes of operation which appear to be feasible. It must be remembered, however, that for these various speeds or cycle times, the interval of closure should be approximately constant. Hence the circumferencial width of the shutter must be adjustable.

   The rapidity of opening and closing will depend upon the peripheral velocity. Hence the

radius of the shutter should be as large as possible.
2. Fuel should be injected only during the desired burning period, because it is desirable to have the burning occur as near the valve end of the tube as possible and only during a short interval. Fuel injection might be accomplished by means of a small injection piston driven by a cam on the valve disc. Although there are many detailed aspects to the design of such a highspeed fluid valve, one of the most important is to keep the injection orfice very near the plunger.

It will be realized that the burning period is not necessarily coincident with the injection period. The time delay between injection and burning is occupied largely by the time required by heating, evaporating, and mixing the fuel with the air. These processes must be expedited. Furthermore, it is probable that no adequate mechanism will be provided by the wave motion for triggering the re-ignition, and it may be expected that the entire system will operate with a great excess of air and therefore much cooler. Therefore, a pilot flame is suggested. The fuel could be sprayed either directly through this flame or against a splash-plate which is kept very hot by the pilot flame. It is known from experience with oscillatory rocket combustion that gasoline-oxygen combustion is capable of extremely high frequency modulation if the right environment is provided.

3.9 PROBLEMS FOR CONTINUING STUDY:

The following aspects of the Analog work require continuing clarification:

3.9.1 Adjustment of I_{S-tot}

The source current has been adjusted so that its average value is zero. This is consistent with the requirement that the total gas flow from the tailpipe be equal to the total gas flow into the valves. However, we do not claim to know to what degree this adjustment simulates the combustion system, however well it may simulate a cold gas system. For this reason we have not made quantitative statements about the <u>percentage</u> improvement in thrust and specific thrust which may be expected from the indicated changes in the Pulse-Jet system, even though the data does give quantitative results. We believe that the proper course for achievement

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of improvement is reliably indicated, but not necessarily the magnitude of the improvement. This is not intended as a pessimistic view, because we can see some reasons why the improvement should be greater than predicted. However, there are too many unanswered questions. For example: If the valve impedance is high in the present engines, why is not the return negative pressure wave larger? Three possible explanations exist; The decrease in gas temperature during this half-cycle, continuation of burning during the period, and large energy dissipation as the wave moves along the walls of the tube. The last possibility can be simulated in the present Analog, the second partly, the first not. However, this discussion serves to indicate that for the present certain adjustments are used with only partial theoretical guidance and considerable intuition. When such factors are involved, it is well to find out what influence on the final results occurs when the arbitrary factor is varied over wide limits. We propose to choose critical points on the graphs of RR-20 and find out how the absolute magnitude of the predicted improvement is altered when the Source Current is adjusted for zero quiescent value.

3.9.2 Internal Resistance

We have not thus far included simulation of the internal drag produced between the flowing gases and the interior of the engine tube. We know that this drag represents negative thrust, but it also increases chamber pressure and hence, to the extent that it is important, will cause chamber pressure or line input voltage to be an erroneous indication of thrust, making it essential to measure thrust from output current. This factor must be investigated.

3.9.3 Backward Resistance of Valves

So far we have studied the effect of Valve Forward Resistance. The value of Valve Backward Resistance, simulating reverse flow through the valves, has been as large as diode characteristics permitted, i.e., the order of .2 to .5 megohms.

It will be difficult in a practical engine to maintain a high ratio of Backward to Forward Resistance. Therefore, we should investigate to what extent our potential gains are reduced by decreasing this ratio in the Analog.

3.9.4 Non-Instantaneous Valve Opening

The present tests using a simple diode for valves have simulated instantaneous valve opening. This can hardly be achieved practically. Therefore, we should find out to what extent the potential improvement is compromised if a few practical types of non-instantaneous opening are simulated, such as a shutter might provide.

3.9.5 Pre-Compression

It is obvious that the use of low impedance valves eliminates the return positive wave which has been thought to be partially responsible for re-ignition in the Pulse-Jet engine. Far more important fundamentally is the question: What role does pre-compression play in the speed of combustion and in the potential efficiency of the operating cycle?

It is customary in all discussions of internal combustion engines to refer to compression ratio as a determinant of cycle efficiency. However, close examination of the derivation of the equations indicates that it is the expansion ratio which is important. The two happen to be the same in the usual engine cycles, but need not be in the Pulse-Jet. Furthermore, there is ample evidence that the compression ratio at which the charge burns in an internal combustion engine varies tremendously as burning proceeds; only that portion which is first ignited burns at the usual compression ratio, while later portions burn at a much higher state of pre-compression. This same mechanism of compression during burning exists in the Pulse-Jet and may be greatly enhanced by more complete scavenging and by the greater inertia of the cool gases. Hence the question: Is compression prior to ignition necessary and essential to the Pulse-Jet cycle? Possibly some single explosion tests can be devised to test this factor.

3.9.6 Other Possibilities

It should be pointed out that the shutter-type valve as suggested for use here, is reminiscent of suggestions which came out of reviews of the German speculation on Pulse-Jet engine possibilities. In fact, the system which has been evolved from the Analog work again suggests the double valve engine, i.e., having exhaust as well as intake valves, as a method of obtaining considerable pre-compression. This point is mentioned here only to indicate that if desired the Analog is capable of rapid inquiry into the efficacy [redacted]

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4.0 CONCLUSIONS

A. It has been shown that the wave motion within a Pulse-Jet tube changes character profoundly depending upon whether the Valve Forward Resistance is greater than or less than Characteristic Resistance. When the valve resistance is low the reverse flow of gases at the tailpipe is avoided, in fact, there is a secondary outflow. This factor promises to eliminate a serious aerodynamic factor in the Pulse-Jet, namely the tailpipe flare, as well as improve the thrust. Similarly, the air intake through the valves is increased by decreasing the resistance to flow and by doubling the number of intake pulses.

B. The properties which permit many modes of operation for a low resistance engine have been discovered, together with the critical conditions for peaks in performance. This study also discloses the determinants of operating frequency, showing that the frequencies of the many possible operating modes are related approximately by the expression

$$f_n = \frac{1}{t + \frac{n}{f_1}}$$

where f_1 is the half-wave mode frequency for the tube, open at both ends, n is a mode number, and t is a delay term which is related to burning time. This series of frequencies is a "stretched sub-harmonic" series.

C. It is shown that the improved performance corelates well with an increase in total gas flow through the tube and with the increase in peak pressure which results from shorter pulse lengths.

D. The design of an experimental engine is discussed, the purpose of which is to test the potential improvements which have been disclosed by the Analog program.

E. Problems requiring continuing study are discussed.

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FIG. 3.2 STUDY OF A PERFORMANCE PEAK

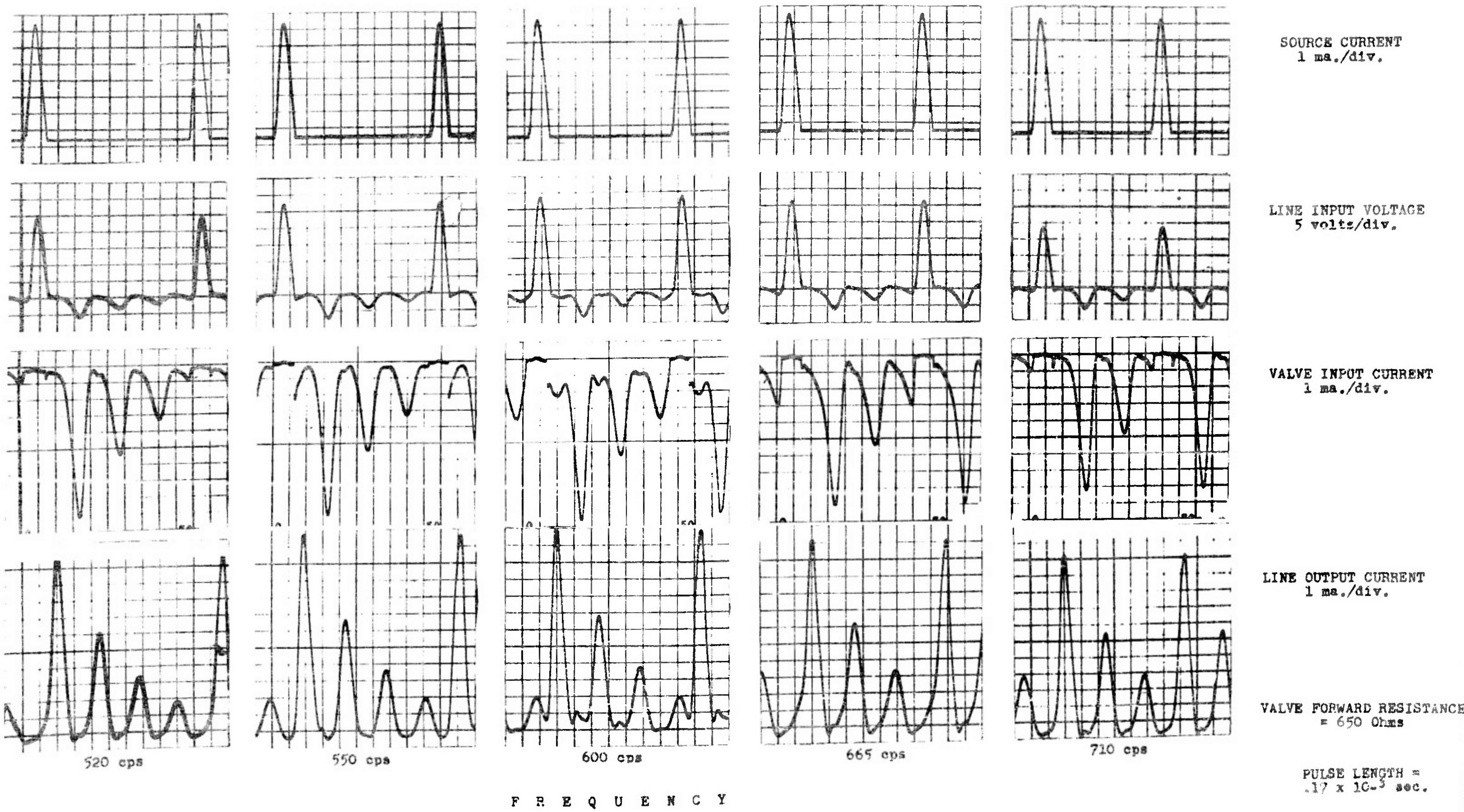
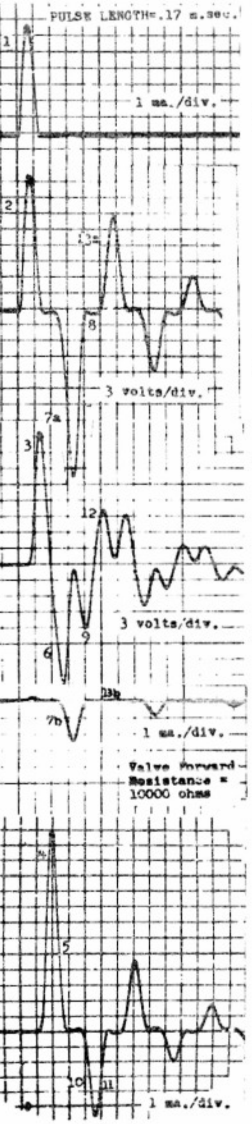


FIG. 3.1 EFFECT OF VALVE TERMINATION ON WAVE MOTION IN A PULSE-JET TUBE

A - VALVE FORWARD RESISTANCE GREATER THAN CHARACTERISTIC RESISTANCE



To be read in numerical order.

SOURCE CURRENT:
1. THE SOURCE CURRENT IS INTRODUCED IN A TIME INTERVAL WHICH IS SMALL COMPARED WITH THE TIME OF TRANSIT DOWN THE LINE.

LINE INPUT VOLTAGE:
2. THE INTRODUCTION OF SOURCE CURRENT CAUSES A RISE IN INPUT VOLTAGE WHICH IS PROPORTIONAL TO CURRENT BECAUSE THE LINE PRESENTS CHARACTERISTIC RESISTANCE TO THE SOURCE. FOR ISOLATED PULSES THE VALUE OF THE VALVE FORWARD RESISTANCE HAS NO INFLUENCE ON THE MAGNITUDE OF THE FIRST VOLTAGE PULSE.

7a. THE NEGATIVE VOLTAGE PULSE HAS RETURNED TO THE VALVE END OF THE LINE. THE AMOUNT OF VOLTAGE WHICH IS DEVELOPED HERE IS PROPORTIONAL TO THE RESISTANCE OF THE OPEN VALVES. IF THERE WERE NO VALVES THE VOLTAGE WOULD BE TWICE THE MAGNITUDE OF THE ORIGINAL PULSE.

8. SINCE THE RESISTANCE IN THIS CASE IS GREATER THAN CHARACTERISTIC, THE NEGATIVE PULSE IS REFLECTED AS A NEGATIVE PULSE.

13a. THE POSITIVE PULSE HAS REACHED THE VALVE END. THIS IS APPROXIMATELY THE TIME AT WHICH IGNITION OF THE FRESH CHARGE SHOULD OCCUR IN THE PULSE-JET.

14. HEREAFTER THE CYCLE REPEATS.

MIDLINE VOLTAGE:
3. THE VOLTAGE PULSE TRAVELS DOWN THE LINE APPEARING A SHORT TIME LATER AT THE MID-POSITION ALONG THE LENGTH.
6. THE RETURNING NEGATIVE VOLTAGE PULSE IS SEEN RETURNING ALONG THE LINE AS IT PASSES THE MID-POSITION.
9. THE REFLECTED NEGATIVE PULSE IS SEEN AT THE MID-POSITION TRAVELING DOWN THE LINE.
12. THE POSITIVE PULSE IS SEEN AT MID-POSITION RETURNING TOWARD THE VALVES.

VALVE INPUT CURRENT:
7b. WHEN THE NEGATIVE VOLTAGE PULSE REACHES THE VALVE END, THE VALVES OPEN INSTANTLY AND ADMIT A PULSE OF CURRENT THROUGH THE VALVES INTO THE LINE. THE AMOUNT OF CURRENT WHICH FLOWS IS INVERSELY PROPORTIONAL TO THE VALVE FORWARD RESISTANCE.
13b. THE VALVES REMAIN CLOSED FOR POSITIVE VOLTAGE SO THAT NO CURRENT FLOWS. (ACTUALLY A SMALL OUTWARD CURRENT APPEARS DUE TO REVERSE RESISTANCE OF THE DIODE. THIS EFFECT MAY BE GREATLY ACCENTUATED IN A PULSE-JET).

LINE OUTPUT CURRENT:
4. AFTER A TIME INTERVAL OF 1/4 MILLISECONDS THE PULSE REACHES THE SHORT-CIRCUITED END OF THE LINE AND APPEARS AS A PULSE OF CURRENT MOVING OUT OF THE LINE. THE VOLTAGE HERE IS NEGLIGIBLE BECAUSE VOLTAGE CANNOT BE DEVELOPED AT A SHORT CIRCUIT. THE MAGNITUDE OF THIS FIRST CURRENT PULSE IS NOT AFFECTED BY THE VALVE FORWARD RESISTANCE.
5. THE LARGE CURRENT PULSE AT THE SHORT-CIRCUITED END OF THE LINE CAUSES A NEGATIVE VOLTAGE WAVE TO RETURN ALONG THE LINE. SUCH A REVERSAL OCCURS AT AN END WHERE THE IMPEDANCE IS LESS THAN CHARACTERISTIC VALUE.
10. THE NEGATIVE VOLTAGE PULSE HAS REACHED THE SHORT-CIRCUITED END OF THE LINE WHERE IT APPEARS AS A PULSE OF CURRENT FLOWING INTO THE LINE. THIS REPRESENTS THE REVERSE FLOW (NEGATIVE THRUST) AT THE TAILPIPE WHICH IS CHARACTERISTIC OF PRESENT PULSE-JET ENGINES.
11. THIS CURRENT PULSE CAUSES ANOTHER REVERSAL OF VOLTAGE RESULTING IN A POSITIVE PULSE BEING RETURNED ALONG THE LINE.

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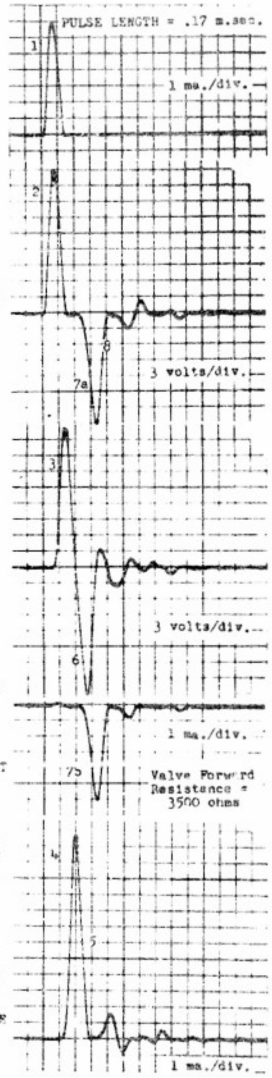
THE OVER-ALL PICTURE: AFTER THE INITIAL POSITIVE REARWARD TRAVELING PULSE, A NEGATIVE PULSE TRAVELS FORWARD, THEN REARWARD, THEN ANOTHER POSITIVE PULSE TRAVELS FORWARD, THEN REARWARD, ETC. THESE GIVE RISE TO ALTERNATE OUTWARD AND INWARD GAS FLOW AT THE EXHAUST, AND AIR INTAKE PULSES ON ALTERNATE TRANSITS.

ANALOGOUS TERMS

Electrical Line	=Pulse-Jet Tube
Input Voltage	=Chamber Pressure
Valve Current	=Air Inflow
Output Current	=Exhaust Gas Flow
Short Circuit	=Open end
Open Circuit	=Closed end

B - VALVE FORWARD RESISTANCE EQUAL TO CHARACTERISTIC RESISTANCE



To be read in numerical order.

SOURCE CURRENT:
1. THE SOURCE CURRENT IS INTRODUCED IN A TIME INTERVAL WHICH IS SMALL COMPARED WITH THE TIME OF TRANSIT DOWN THE LINE.

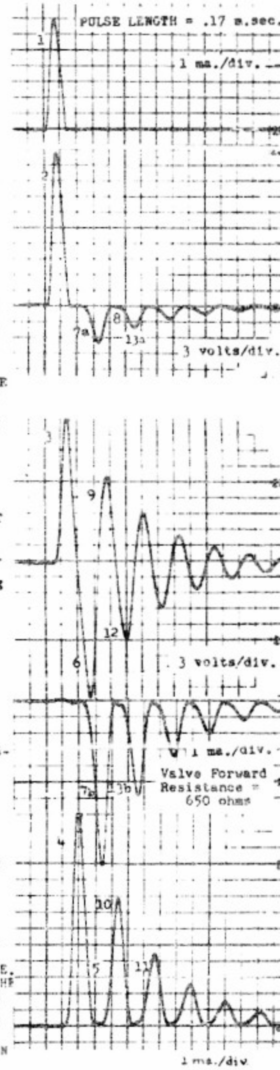
LINE INPUT VOLTAGE:
2. THE INTRODUCTION OF SOURCE CURRENT CAUSES A RISE IN INPUT VOLTAGE WHICH IS PROPORTIONAL TO CURRENT, BECAUSE THE LINE PRESENTS CHARACTERISTIC RESISTANCE TO THE SOURCE. FOR ISOLATED PULSES, THE VALUE OF THE VALVE FORWARD RESISTANCE HAS NO INFLUENCE ON THE MAGNITUDE OF THE FIRST VOLTAGE PULSE.
7a. THE NEGATIVE VOLTAGE PULSE HAS RETURNED TO THE VALVE END OF THE LINE.
8. SINCE THE RESISTANCE IN THIS CASE IS EQUAL TO CHARACTERISTIC VALUE THE NEGATIVE PULSE IS NOT REFLECTED BECAUSE THE ENERGY IS COMPLETELY DISSIPATED. (OUR ELECTRICAL LINE IS NOT A CONTINUOUS LINE BUT IS A DUMMY LINE CONSISTING OF LUMPED PARAMETERS WHICH REPRESENTS A CONTINUOUS LINE ONLY APPROXIMATELY. HENCE SOME REFLECTION DOES OCCUR). HERE THE PHENOMENON CEASES IN THIS CASE.

MIDLINE VOLTAGE:
3. THE VOLTAGE PULSE TRAVELS DOWN THE LINE APPEARING A SHORT TIME LATER AT THE MID-POSITION ALONG THE LENGTH.
6. THE RETURNING NEGATIVE VOLTAGE PULSE IS SEEN RETURNING ALONG THE LINE AS IT PASSES THE MID-POSITION.

VALVE INPUT CURRENT:
7b. WHEN THE NEGATIVE VOLTAGE PULSE REACHES THE VALVE END, THE VALVES OPEN INSTANTLY AND ADMIT A PULSE OF CURRENT THROUGH THE VALVES INTO THE LINE. THE AMOUNT OF CURRENT WHICH FLOWS IS INVERSELY PROPORTIONAL TO THE VALVE FORWARD RESISTANCE.

LINE OUTPUT CURRENT:
4. AFTER A TIME INTERVAL OF 1/4 MILLISECONDS THE PULSE REACHES THE SHORT-CIRCUITED END OF THE LINE AND APPEARS AS A PULSE OF CURRENT MOVING OUT OF THE LINE. THE VOLTAGE HERE IS NEGLIGIBLE BECAUSE VOLTAGE CANNOT BE DEVELOPED AT A SHORT CIRCUIT. THE MAGNITUDE OF THIS FIRST CURRENT PULSE IS NOT AFFECTED BY THE VALVE RESISTANCE.
5. THE LARGE CURRENT PULSE AT THE SHORT-CIRCUITED END OF THE LINE CAUSES A NEGATIVE VOLTAGE WAVE TO RETURN ALONG THE LINE. SUCH A REVERSAL RESULTS AT AN END WHERE THE IMPEDANCE IS LESS THAN CHARACTERISTIC VALUE.

C - VALVE FORWARD RESISTANCE LESS THAN CHARACTERISTIC RESISTANCE



To be read in numerical order.

SOURCE CURRENT:
1. THE SOURCE CURRENT IS INTRODUCED IN A TIME INTERVAL WHICH IS SMALL COMPARED WITH THE TIME OF TRANSIT DOWN THE LINE.

LINE INPUT VOLTAGE:
2. THE INTRODUCTION OF SOURCE CURRENT CAUSES A RISE IN INPUT VOLTAGE WHICH IS PROPORTIONAL TO CURRENT, BECAUSE THE LINE PRESENTS CHARACTERISTIC RESISTANCE TO THE SOURCE. FOR ISOLATED PULSES, THE VALUE OF THE VALVE FORWARD RESISTANCE HAS NO INFLUENCE ON THE MAGNITUDE OF THE FIRST VOLTAGE PULSE.
7a. THE NEGATIVE VOLTAGE PULSE HAS RETURNED TO THE VALVE END OF THE LINE. THE AMOUNT OF VOLTAGE WHICH IS DEVELOPED HERE IS PROPORTIONAL TO THE RESISTANCE OF THE OPEN VALVES.
8. SINCE THE RESISTANCE IN THIS CASE IS LESS THAN CHARACTERISTIC, THE NEGATIVE PULSE IS REFLECTED AS A POSITIVE PULSE. SINCE THE VALVES ARE OPEN DURING THIS INVERSION, NO VOLTAGE IS DEVELOPED AT THE VALVES. THE PROOF OF THE POSITIVE PULSE REFLECTION APPEARS ALONG THE LINE. (See 9)
13a. A NEGATIVE PULSE HAS AGAIN REACHED THE VALVE END.
14. HEREAFTER THE CYCLE REPEATS

MIDLINE VOLTAGE:
3. THE VOLTAGE PULSE TRAVELS DOWN THE LINE APPEARING A SHORT TIME LATER AT THE MID-POSITION ALONG THE LENGTH.
6. THE RETURNING NEGATIVE VOLTAGE PULSE IS SEEN RETURNING ALONG THE LINE AS IT PASSES THE MID-POSITION.
9. THE REFLECTED POSITIVE PULSE IS SEEN AT THE MID-POSITION TRAVELING DOWN THE LINE.
12. THE NEGATIVE PULSE IS SEEN AT MID-POSITION RETURNING TOWARD THE VALVES.

VALVE INPUT CURRENT:
7b. WHEN THE NEGATIVE VOLTAGE PULSE REACHES THE VALVE END, THE VALVES OPEN INSTANTLY AND ADMIT A PULSE OF CURRENT THROUGH THE VALVES INTO THE LINE. THE AMOUNT OF CURRENT WHICH FLOWS IS INVERSELY PROPORTIONAL TO THE VALVE FORWARD RESISTANCE.
13b. THE VALVES AGAIN OPEN OR REMAIN OPEN, ADMITTING A SECOND CHARGE OF VALVE CURRENT. SINCE THE VOLTAGE DOES NOT GO POSITIVE DURING INTERVALS BETWEEN PULSES, IT IS IMMATERIAL WHETHER THE VALVES CLOSE OR NOT. THEY NEED BE CLOSED (OR EVEN PRESENT) ONLY DURING THE INITIAL CURRENT PULSES (EXPLOSION).

LINE OUTPUT CURRENT:
4. AFTER A TIME INTERVAL OF 1/4 MILLISECONDS THE PULSE REACHES THE SHORT-CIRCUITED END OF THE LINE AND APPEARS AS A PULSE OF CURRENT MOVING OUT OF THE LINE. THE VOLTAGE HERE IS NEGLIGIBLE BECAUSE VOLTAGE CANNOT BE DEVELOPED AT A SHORT CIRCUIT. THE MAGNITUDE OF THIS FIRST CURRENT PULSE IS NOT AFFECTED BY THE VALVE FORWARD RESISTANCE.
5. THE LARGE CURRENT PULSE AT THE SHORT-CIRCUITED END OF THE LINE CAUSES A NEGATIVE VOLTAGE WAVE TO RETURN ALONG THE LINE. SUCH A REVERSAL OCCURS AT AN END WHERE THE IMPEDANCE IS LESS THAN CHARACTERISTIC VALUE.
10. THE POSITIVE VOLTAGE PULSE HAS AGAIN REACHED THE SHORT-CIRCUITED END OF THE LINE WHERE IT APPEARS AS A SECOND PULSE OF OUTWARD FLOWING CURRENT. THIS IS A SECOND PULSE IN THE PROPER DIRECTION FOR THRUST.
11. THIS CURRENT PULSE CAUSES ANOTHER REVERSAL OF VOLTAGE PULSE, RESULTING IN ANOTHER NEGATIVE PULSE BEING RETURNED ALONG THE LINE.

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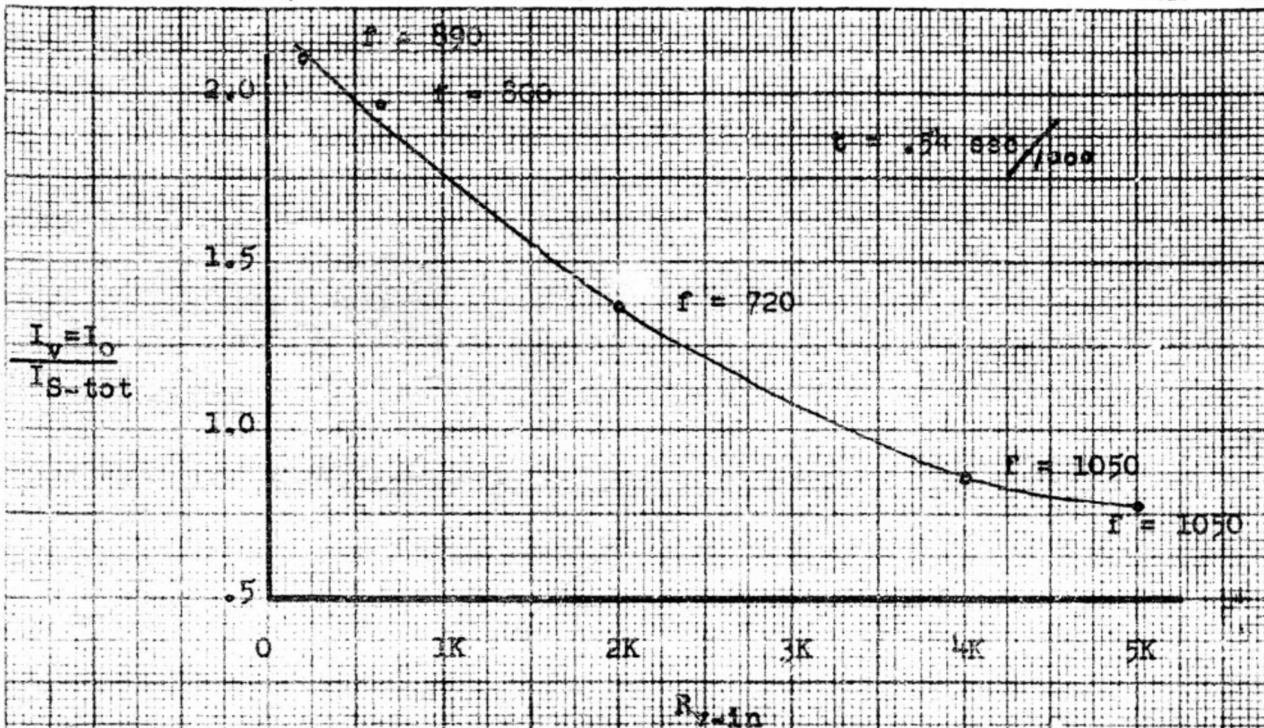
THE OVER-ALL PICTURE: ALTERNATE POSITIVE REARWARD TRAVELING PRESSURE PULSE AND NEGATIVE FORWARD TRAVELING PULSE CAUSING ALTERNATELY - OUTWARD-FLOWING EXHAUST GAS PULSES AND INWARD-FLOWING AIR INTAKE PULSES. NEW ENERGY CAN BE ADDED AFTER ANY OF THESE INTAKE PULSES.

COMPARISON - C vs. A

IN THE CASE OF LOW VALVE IMPEDANCE, BOTH THE VALVE INTAKE AIR FLOW PULSES AND THE EXHAUST GAS OUTFLOW PULSES ARE OF MUCH GREATER MAGNITUDE. THE EXHAUST PULSES ARE ALL IN THE SAME DIRECTION AND THE AIR INTAKE PULSES OCCUR TWICE AS OFTEN. HENCE THE AVERAGE GAS FLOW IS VERY GREATLY INCREASED. CORRESPONDINGLY, THE AVERAGE CHAMBER PRESSURE IS GREATER BECAUSE AFTER THE LARGE INITIAL PULSE ONLY SMALL NEGATIVE PULSES OCCUR.

IN CASE A, IT IS CLEAR THAT RE-IGNITION OF FRESH CHARGE CAN OCCUR WHEN THE CHAMBER PRESSURE GOES POSITIVE WITH ANY RETURNING POSITIVE PULSE - BECAUSE BOTH POSITIVE PRESSURE AND POSITIVE SLOPE OCCUR.

IN CASE C, THE PRESSURE DOES NOT AGAIN GO POSITIVE. HOWEVER, THE SLOPE DOES GO POSITIVE RECURRENTLY WITH EACH INTAKE PULSE. HENCE ONLY SLOPE TRIGGERING IS AVAILABLE FOR RE-IGNITION.



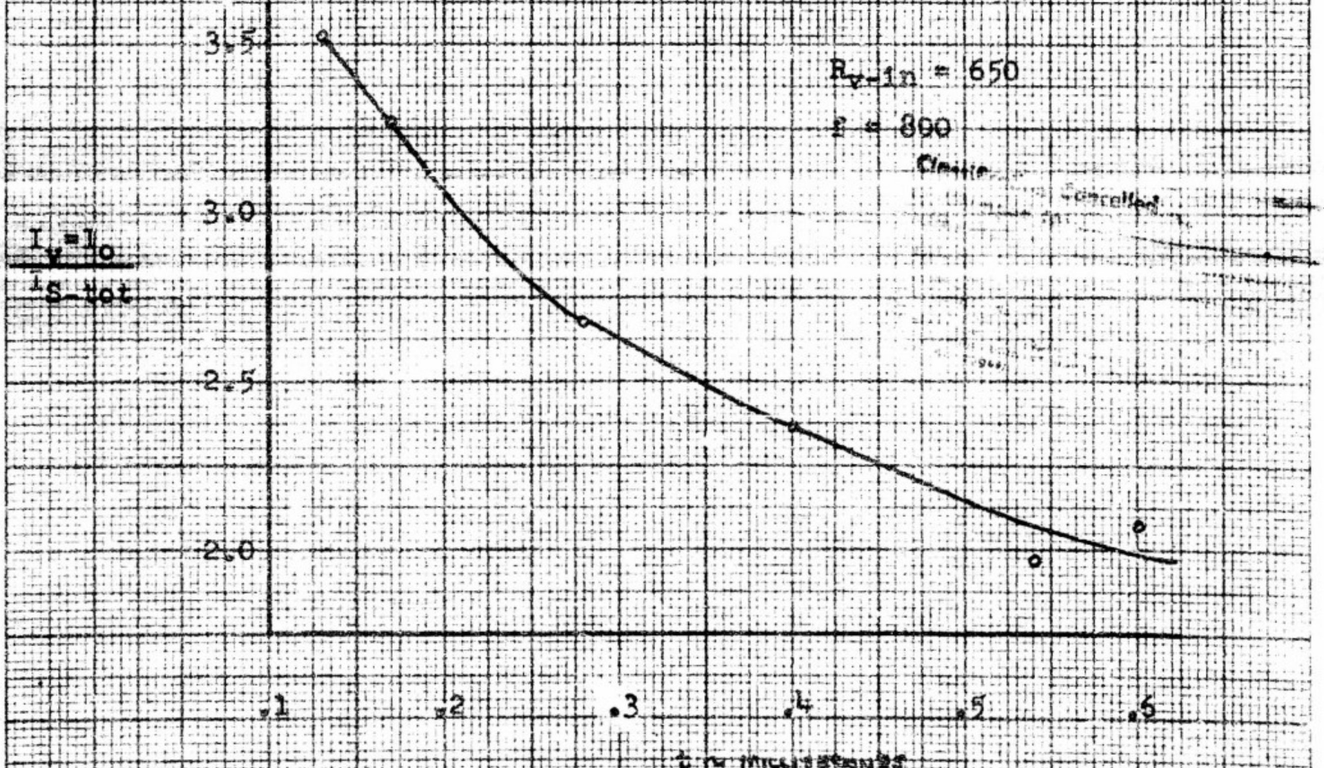


FIGURE 3.3 INFLUENCE OF VALVE FORWARD RESISTANCE AND INPUT PULSE LENGTH ON VALVE AND OUTPUT CURRENT FLOW.